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PATUXENT RIVER, MARYLAND

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HIGHLY DAMPED STRUCTURE PART II

by

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4 December 1997

Structures Division
Tactical Aircraft Strength Branch
Naval Air Warfare Center Aircraft Division
Patuxent River, Maryland

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This report describes a research and development program whose goal was the development of vibration and fatigue resistant structure. The approach was based on the application of passive damping technology to the redesign of structural components. The specific components addressed included the skins of the beavertail section of the F-14D and the spars of a half-scale test bed of the F/A-18 vertical tails. Integrally damped structure was achieved through the cocuring of damping materials with advanced composites. The results show that benefits can be obtained by including damping as a parameter in the design of parts that experience dynamic loads.

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ABSTRACT

This report describes a research and development program whose goal was the development of vibration and fatigue resistant structure. The approach was based on the application of passive damping technology to the redesign of structural components. The specific components addressed included the skins of the beavertail section of the F-14D and the spars of a half-scale test bed of the F/A-18 vertical tails. Integrally damped structure was achieved through the cocuring of damping materials with advanced composites. The results show that benefits can be obtained by including damping as a parameter in the design of parts that experience dynamic loads.

ACKNOWLEDGMENT

The authors gratefully acknowledge the technical assistance of Lee Rosenstadt who fabricated the damped leading edge spar, and Michael Bosak and Dickson Alley who developed the fabrication methods described in this report.

CONTENTS

SECTION 1
INTRODUCTION

1.1 BACKGROUND

During the first phase of this project, the Strength Branch of NAWCAD Warminster, Pennsylvania, under the sponsorship of the Office of Naval Research, developed and demonstrated new design concepts for passively damped structural components (reference 1). (For background information on passive damping technology, see references 2 and 3). This work was performed through two separate collaborations; one was with the McDonnell Douglas Corporation, Government Aerospace-East (MDAE), which through a corporate merger has become Boeing - St. Louis, and the other was with the Northrop-Grumman Corporation (Grumman).

With MDAE, NAWCAD Warminster designed and fabricated a passively damped trailing edge spar. The performance of this spar was evaluated on a test bed that was designed as a half-scale version of the F/A-18 vertical tail torque box. The results of these tests were encouraging in that the damping of the test bed's fundamental bending mode was increased by more than threefold. Although this significant increase in damping was achieved, low overall damping values prevailed. This was to be expected since only one of four aluminum spars was replaced with a damped spar and since a structural adhesive, instead of a damping material, was selected to provide the damping. Subsequently, a leading edge spar was designed and built. The leading and trailing edge spars were then mounted and tested together in the test bed in order to examine how the structural damping would scale and to see if this particular arrangement would lead to a useful level of damping in the first torsional mode. The results of this second effort are recorded in this report.

In support of the Grumman effort, NAWCAD Warminster developed designs for damped skin panels that were to be applied in an overall redesign of the beavertail section of the F-14D aft center body fuselage. The damped skin designs were evaluated by Grumman and incorporated into a finite element model of a double bay size access panel. The finite element analysis predicted that substantial improvements in fatigue life would be achieved. This increase in life became the basis for eliminating a midframe support from the redesign in order to reduce structural weight. NAWCAD Warminster also performed high temperature stiffness, strength, and damping tests in order to evaluate the performance of various commercially available damping materials. The results of these tests showed that highly damped graphite/epoxy skins could be provided in the desired range of frequency and temperature.

The original plan for the joint Grumman-NAWCAD Warminster effort was to build and test a damped beavertail. Because Grumman's internal research and development budget was subsequently reduced and because of the uncertainties created by the merger of the Grumman Corporation with the Northrop Corporation, this original plan was scaled back. NAWCAD Warminster continued with the program by building two damped skin panels in accordance with the structural drawings provided by Grumman. Arrangements were then made to test these panels in a high temperature acoustic environment at the Structural Dynamics Test Facility of Wright

Laboratories (references 4 and 5). Because this facility had other pressing commitments, the panel tests were delayed for more than a year. In the meantime, the corporate merger of Northrop and Grumman was completed, and Grumman again became involved in the damping program by providing undamped baseline panels to Wright Laboratories. The results of the fabrication and panel test efforts are also recorded in this report.

1.2 PROGRAM OBJECTIVE

Naval aircraft experience intense vibrations that lead to vexing in-service structural problems. Designers are being increasingly challenged to provide economical structural components that can endure these vibrations. The objective of the Highly Damped Structure program was to demonstrate that damping technology could be used to develop structural parts with improved vibration resistance. The expectation is that these parts will lead to improved performance and lifetime integrity.

SECTION 2
RESULTS AND DISCUSSION

2.1 F/A-18 DAMPED SPAR PROGRAM

2.1.1 BACKGROUND

The high angle of attack maneuvers of the F/A-18 produce turbulent airflow that strikes structural components. The vibrations induced by this airflow have lead to structural fatigue and damage. In response to these problems, MDAE has conducted a number of investigations with the goal of reducing the destructive vibrations. Some of these efforts have involved the application of passive damping technologies (reference 6). To aid in the evaluation of various vibration control concepts, MDAE built a test bed that mimics the dynamic characteristics of the F/A-18 vertical tails. NAWCAD Warminster constructed a damped trailing edge spar to be evaluated on this test bed and then in a subsequent effort provided a damped leading edge spar.

2.1.2 DESIGN, FABRICATION, AND TESTING

A sketch of the half-scale vertical tail test bed is shown in figure A-1. The all aluminum construction consists of four spars, a three-piece midrib, a rigid base fixture, and thin gage skins that are mechanically fastened to the spars and to the ribs. Reinforced angles are bolted to the base fixture to provide an attachment to the test table.

The damped leading edge spar (Spar No. 1 of figure A-1) is shown mounted in the test bed in figure A-2. The overall dimensions of the spar are shown in figures A-3 and A-4. The construction of the leading edge spar was similar to that of the trailing edge spar in that two angles were bonded together with a damping material to form a channel. The angles consisted of nine plies of Hexcel carbon/epoxy prepreg fabric.

The damping material used was 3M's Y-9469 film adhesive. The shear modulus and damping properties of this material are shown in figure A-5. Under flexure and torsion, the deformations of the angles are expected to shear the film adhesive and thereby provide a means for dissipating vibrational energies. The combination of damped leading and trailing edge spars was also intended to increase the damping of the test bed's first torsional mode.

The trailing edge spar had been built using 3M's AF-32 structural adhesive as the damping material. The use of Y-9469 was recommended by MDAE based on an approximate finite element analysis of the test bed. Y-9469 has a much lower shear modulus than AF-32, but it has a higher loss factor.

The spar was fabricated by cocuring the Y-9469 damping layer with the layers of graphite/epoxy fabric. Y-9469 did not present any unusual difficulties in handling during the fabrication.

To form the spar, a special mandrel (reference 1) was made upon which the plies were laid by hand. Initial difficulties were encountered with a "wrap around" bagging method. In its first form, the bag consisted of two separate trilayered sheets joined and sealed with tacky tape. The three layers in the sheets were a nonporous release film, a breather ply, and a barrier bagging film. During the cure, the seams of the bag caught and bent the ends of the flanges. A slight depression also formed on the outside face of the web, in the area where the layup covered the knob of the mandrel. To avoid these difficulties, the height of the knob on the mandrel was increased and the wrap was changed to a single trilayered bag. The tacky tape seal and the seam of the bag were positioned at the base of the mandrel, away from the edges of the flanges.

Difficulties were also encountered when the trailing edge spar was removed from its mandrel. To avoid this problem, the mandrel of the leading edge spar was wrapped with a flash tape coated with Free Kote 700. This produced a very effective tool release surface. (Tedlar was not used because its positional instability could have caused kinks that would have marred the finish of the spar.) Care was taken to not overlap the seams of the flash tape as this would have transferred an impression to the finished product. Also, the appearance of the trailing edge spar had been marred by an aged release film that could not be readily removed from the surface of the spar (see reference 1, figures 13 and 14). This problem was avoided with the use of a newly acquired film (see figure A-6).

Once these basic procedures were worked out, no exceptional difficulties were encountered during the fabrication. The processing was performed using a typical cure cycle. Figure A-7 shows that the damping layer had bonded well with the fabric, it retained its dimensions, and none of the damping material was absorbed into the epoxy. There was no evidence of thermal degradation.

The formation of voids is always a concern when dealing with laminated materials. In previous work (references 1, 7, and 8), visual inspections, photomicrographs, and C-scans showed that damping materials could be cocured with advanced composite materials without the formation of voids. However, figure A-8 shows several voids in a section trimmed from the 1 in. end of the leading edge spar. Figure A-9 shows these same voids at a higher level of magnification. Figure A-10 is a photomicrograph of a section trimmed from the 2 in. end of the spar. Although most of the damping layer is seen to be void free, a blemish (shown in figure A-11) is interpreted as a subsurface void. An A-scan of the spar did not reveal any voids in the bond line. Therefore, it was felt that the voids in figures A-8 through A-11 were anomalies due to the evacuation of air at the ends of the piece. After removing the trim, the ends of the spar were not inspected.

Another area of concern was for the inner and outer angles to remain physically separated by the damping layer. (If the angles fused together, then the damping layer would not experience the intended level of shearing during spar flexure). This requirement was satisfied in the interior of the bonded area since the damping layer retained its thickness. Visual inspection of the two seams showed that the inner and outer angles had remained separated although there was a slight pinching of the damping layer on the inside of the web at the 1 in. end of the spar. Figure A-12 is a photomicrograph of the trim taken from this area. (Figure A-12 also shows several edge voids.) Figure A-13, a photomicrograph of the other end of the web, shows the desired edge detail with a lip of damping material separating the inner and outer angles.

In all of the photomicrographs, and especially in the bends of the angles, the graphite/epoxy exhibits porosity. This was expected because the fabric was from older stock and since no special precautions were taken to form the bends. Using this inferior material for the damping demonstration was acceptable since the spar was to be subjected to dynamic response testing and not to static strength tests.

After curing and trimming, the spar was supported in a vertical position with its wider end at the base. The support was a clamp with an adjustable grip. The approximate modal properties for this cantilevered configuration were determined using an instrumented force hammer and an accelerometer. The clamp and the direction of the strike were applied to both the major and minor axes of the spar. The results of these tests are shown in table B-1. The spar had good damping properties.

After shipping to MDAE, the spar was machined for placement into the test bed, and holes were drilled into its flanges to accept fasteners for attaching the skins. Figure A-2 shows the completed assembly mounted in a vertical position on a Ling 340 shaker table. This table provides a harmonic horizontal motion.

A modal survey (mode shapes, damped frequencies, and modal damping) of the "all-aluminum" test bed was performed by MDAE in 1992. The modal survey was based on readings from an impact hammer test using an instrumented force hammer and accelerometers. This test was repeated in 1994 with the aluminum trailing edge spar replaced by a damped composite spar (reference 9). A shaker was also used to perform sine sweep testing at levels of excitation of "1/10 g" and "1 g". In 1995, these tests were repeated with both the leading and trailing edge aluminum spars replaced by damped composite spars (reference 10). The results of all these tests are shown in tables B-2 and B-3. The damping values listed in these tables were calculated using the half-power method. The transfer functions from the sine swept "Two Damped Spar" tests were further processed by circle fitting in the Nyquist plane. This yielded a more accurate estimate of the modal values. The results of these calculations are shown in table B-4. What is deemed to be the best data is summarized for comparison in table B-5.

The results of the "One Damped Spar" test show a significant drop in the natural frequency of the first bending mode. This drop implies that the clamp-up condition for this test was inadequate. Also, the "1 g Sine Sweep" test shows a slight further reduction in the natural frequencies for the "One Damped Spar" case. This was probably due to a feedback between the shaker table and the test bed that was dependent upon the load levels in the armature of the shaker table. The results also indicate that the support conditions were improved in the "Two Damped Spars" test.

There are substantial differences in the damping data reported in the tables. Generally, at higher levels of damping, the shaker test yields more accurate modal information than the impact hammer test because the shaker can concentrate energy into specific modes of response.

In spite of the boundary condition, the data for the "One Damped Spar" test shows that the damping in the first bending mode was increased by approximately a factor of three. The results for the first torsional mode were inconclusive, short of saying that the damping was increased.

The most accurate estimates of the damping for the "Two Damped Spar" configuration are the values listed in table B-4. It is seen that substantial values of damping had been achieved in all modes including the first bending and the first torsional modes. The mode shapes in the higher modes of response exhibited a semicoupling due to the high levels of damping. Note that the reduction in natural frequencies are due to a loss of static stiffness from the use of the damped spars. Nevertheless, the high damping indicates that there is a greatly improved dynamic stiffness.

2.1.3 INFERENCE

The aerodynamic damping that the vertical tail experiences is estimated to be 0.02 to 0.04 viscous damping (equivalent to loss factors of 4 to 8%). For a damping redesign to be successful, it should be capable of roughly doubling the total system damping by matching the aerodynamic damping with a comparable amount of structural damping. Doubling the system damping of a linear dynamic system would reduce the rms response by approximately 30%. Table B-5 shows that the "Two Damped Spars" case achieves this level of damping for all but the fundamental bending mode.

For the F/A-18 vertical tail, at a 25% steady state load, a 30% rms reduction translates into a Life Improvement Factor (LIF) of three in the first bending mode and five in the first torsion mode (reference 11). These estimated LIF's are based on the high cycle random fatigue properties of 2024 aluminum. The "overall" life extension brought about by increased damping can only be determined by a complete fatigue analysis that considers the response and time spent in each flight condition.

The F/A-18 vertical tails experience a severe dynamic environment that has resulted in numerous maintenance actions. If the results presented in table B-5 are scaleable to a full-size vertical tail and if the damping designs can be made to satisfy the stiffness and strength requirements, then more durable and dynamically improved parts can be provided to resist this environment.

2.2 F-14D DAMPED BEAVERTAIL PROGRAM

2.2.1 BACKGROUND

Oscillatory sonic pressures are the most critical loads experienced by the beavertail portion of the aft centerbody fuselage. In-flight measurements yield a peak pressure reading of 156 dB when the speedbrake is deployed. This occurs at an altitude of 14,000 ft with the aircraft flying at Mach 1.24 (reference 12). The recovery temperature associated with this condition is 235°F. It is estimated that the beavertail will be exposed to this environment for a total of 3.12 hr over the life of the aircraft. As a rule-of-thumb, the fatigue of thin gage structure usually occurs at 145 dB.

Because of the high acoustic loads, the design of the beavertail was modified several times before arriving at its final configuration. As a result, all of the F-14D aircraft are fitted with an aerodynamically improved all-aluminum beavertail that contains sonic fatigue resistant design features. These structural modifications resulted in a considerable increase in component weight and nose ballast.

To reduce the weight and to improve the life cycle costs of the beavertail, Grumman proposed an all-composite redesign of the tail. Then, in collaboration with NAWCAD Warminster, they undertook a program in which the redesign was to incorporate new structural damping technologies. Preliminary design work, material evaluations, analytical modeling (finite element analysis), fatigue life calculations, and fabrication studies were performed. This effort, which would have resulted in the design, fabrication, and testing of a full-scale damped beavertail, was interrupted by Grumman's corporate merger and reorganization with the Northrop Corporation.

In the preliminary study, the sonic fatigue analysis of the damped skin panels showed that these panels had ample fatigue life. By taking advantage of this prediction, Grumman proposed eliminating midframe supports to achieve further weight and cost savings. An analysis of this redesign showed that the particular double bay skin panel had twice the required life. In the follow-on portion of the damping program, NAWCAD Warminster constructed damped panels from detail drawings provided by Grumman. In order to verify Grumman's life predictions, these panels were tested in a high temperature acoustic environment.

2.2.2 DESIGN, FABRICATION, AND TESTING

Detailed design drawings of the damped skin panels are shown in figures A-14 and A-15. The materials used in the construction were IM7/977-3 graphite epoxy tape and ISD-110 acrylic polymer damping film. The material properties of a unidirectional ply of IM7/977-3 are listed in table B-6. The thickness of the plies was nominally 5.6 mils. ISD-110 is commercially available as a 5 mil film and was developed by 3M to have peak damping properties between 100 and 210°F. The material properties of ISD-110 are shown in figure A-16 and in table B-7. ISD-110 is tack free at room temperature and requires heat and pressure to develop adequate bonding. In previous work, it handled well and readily bonded to graphite-epoxy (reference 1).

Because ISD-110 was tack free, it did not stick to the graphite-epoxy plies during lay-up. Therefore, the backing had to be removed from the film before it was placed. Care was taken to avoid stretching the film. In retrospect, a heat gun could have been used to raise the temperature of the film so that it would stick to the lay-up and allow a controlled removal of the backing. Otherwise, the panels were laid-up without any unusual difficulties. They were then bagged using the bagging order shown in figure A-17. The panels were cured in an autoclave using a typical cure cycle (see table B-8).

After curing, the panels were inspected for voids. C-scans showed that the ISD-110 film had achieved good bonding during the cure process (figures A-18 and A-19). A photomicrograph of the trim from the panel is shown in figure A-20. As with other cocured fabrications using 3M damping materials, there was no evidence of excessive flow, absorption into the epoxy, or thermal degradation of the damping material.

The panels were shipped to Wright Laboratories for testing. The tests were performed in the High Temperature Acoustic Subelement Chamber (figure A-21). The funding for the tests came from the Extreme Environmental core area of Wright Laboratory. (The Navy provided a nominal amount of support for the tests through a MIPR.)

One baseline aluminum panel, two baseline graphite/epoxy panels, and two damped graphite/epoxy panels were tested. Room and elevated temperature (235°F) sine sweeps were performed at 130 to 140 dB. Room and elevated temperature acoustic responses were recorded at 140 to 158 dB. Finally, an elevated temperature sonic fatigue test was planned to be performed at 158 dB for 10 hr. Wright Laboratories reported that the damped plates exhibited good damping properties at elevated temperature. Typical data plots are shown in figures A-22 (undamped panels) and A-23 (damped panels) (reference 13).

A post-test inspection found delaminations in the damped plates. During the subsequent engineering investigation, it was discovered that the strain sensors were installed on the plates with an adhesive system having an application temperature of 390°F. It is known that the damping material ISD-110 can withstand sustained temperatures of up to 250°F. During fabrication, the damping layer was subjected to sustained temperatures of 355°F. (Note that in the autoclave, the damping layer is shielded from the atmosphere by the bagging material and the graphite/epoxy.) In previous work (reference 1), ISD-110 survived the autoclave environment with its damping and bonding properties intact. However, 3M product literature warns that in no instance should ISD-110 be subjected to temperatures in excess of 380°F (reference 14). In spite of the shielding provided by the graphite/epoxy layers during the installation of the strain gages, the damping layer probably experienced temperatures at or beyond this limiting value.

The engineering investigation concluded that the delaminations formed during the installation of the strain gages. In the tests, the damping treatment performed well but the delaminations continued to grow. At the conclusion of the test effort, the delaminations had become quite extensive. Because of the delaminations, Wright Laboratories deemed the tests invalid. They have never reduced the data nor issued a final report.

2.2.3 INFERENCE

The beavertail is a thin gage component that experiences high temperatures and intense sonic loads. It is representative of many secondary structural components whose designs are driven by dynamic loads. The use of damping technology in the design of these parts offers a way of providing lifetime integrity at reduced structural weight.

In the first phase of this study, analysis and experiment were used to show that highly damped graphite-epoxy skins could be provided for the required range of frequencies and temperature. Therefore, subject to strength and stability requirements, highly damped skin designs were available for the beavertail redesign. Grumman's analysis and design efforts predicted significant weight and cost savings that would be achieved through double bay skin panels, reduced part count, cocured assembly, and reduced ballast.

The effort planned for the second phase of this study was curtailed. Instead of a full-scale demonstration, the project was limited to the design, fabrication, and testing of skin panels. Although the test results were rendered invalid by the presence and growth of delaminations, it can be concluded that the damping treatment provided vibration resistance and would have reduced the transmission of vibrational energies to the substructure.

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SECTION 3
CONCLUSIONS

In the first and second phases of this study, damped structural elements were designed, analyzed, and tested. The elements included both primary and secondary structural parts that are representative of parts found on naval aircraft. These applications extend the technology of integrally damped cocured structure.

The results of this project indicate that benefits can be obtained by including damping as a parameter in the design of parts that are to experience dynamic loads. Through this approach, future structural components can be optimized for weight and structural integrity so that chronic vibration-related maintenance problems can be avoided. Doing so could lead to substantial O&M cost savings for the Navy (references 15 and 16).

The Northrop-Grumman Corporation is using the results of this project in their "Buffet Fatigue Resistant Structure" program in which they plan to reapply the technology to an F/A-18 E/F part. It is their intention to select a component for full-scale redesign, fabrication, and testing. Their long-term interest is to extend the technology to the JSF vehicle with particular application to the lower fuselage area of the STOVL version of this fighter.

In their IRAD program, Boeing - St. Louis is continuing their damping work with the study of damped bonded repairs, damped stiffener treatments, and damped composite patches.

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REFERENCES

1. Barrett, D. J., Ray, H., and Arocho, A., "Highly Damped Structure," Report No. NAWCADWAR-94126-60, of Jun 1994.

2. Soovere, J. and Drake, M. L., "Aerospace Structures Technology Damping Design Guide," AFWAL-TR-84-3089, 1985.

3. Nashif A. D., Jones D. I. G., and Henderson J. P., "Vibration Damping," New York: John Wiley and Sons, 1985.

4. Pearson, Jerome, "High Temperature Acoustic Test Facilities and Methods," AGARD Conference Proceedings 549, of Sep 1994.

5. Shimovetz, R. H., and Wentz, K. R., "High Intensity Acoustic Testing of Flight Structures", Facility Description of the Structural Dynamics Facility at Wright Laboratories.

6. Liguore, S., Ferman, M., and Yurkovich, R., "Integral Damping Treatments for Primary Aircraft Structures," Paper BAA, Proceedings of Damping '91, AFWAL-TR-91-3078, of Aug 1991.

7. Rotz, C. A. and Barrett, D. J., "Co-Cured Damped Layers in Composite Structure," SAMPE Quarterly Journal, of Jan 1992, Vol. 23, No. 2, pp. 43-47.

8. Harvey, J. A., Koury, J. L., Kim, T. D., and Drake, M. L., "Integrally Damped Composites - A Study on Fabrication, Dynamics and Static Effects," SPIE Vol. 1917, Smart Structures and Intelligent Systems, pp. 634-644, 1993.

9. "Smart Skins Torque Box Vibration Test," MDAE Technical Memorandum 253.94.0054.01, of Apr 1994.

10. "Vibration Test of the Half Scale Torque Box: Damped Spars and Smart Skin Evaluation," MDAE Technical Memorandum 253.95.0110.01, of Aug 1995.

11. Liguore, S., "Calculations for Life Improvement Factor," Facsimile transmission to NAWCAD Warminster, of 20 Oct 1995.

12. Parente, C., "Appendix C: Aircraft 87 and On Structure," Grumman Aerospace Corporation Report A55-338-R-89-01, of 28 Feb 1989.

13. Wentz, K., "F-14 Beavertail Integrally Damped Structure," Status Presentation, Facsimile transmission to NAWCAD Patuxent River, of 14 Jan 1997.

14. "Scothdamp™ Vibration Control System" 3M Technical Service Bulletin 88-1.

15. Drake, M. L., "Passive Damping Impact on Air Force System Maintenance Costs," in The Role of Damping in Vibration and Noise Control, New York: ASME Publication DE-Vol. 5, 1987, pp. 75-80.

16. Vacca, S. N., "Demonstration of Damped Structure for Increased Supportability and Reliability," in The Role of Damping in Vibration and Noise Control, New York: ASME Publication DE-Vol. 5, 1987, pp. 81-87.

APPENDIX A
FIGURES

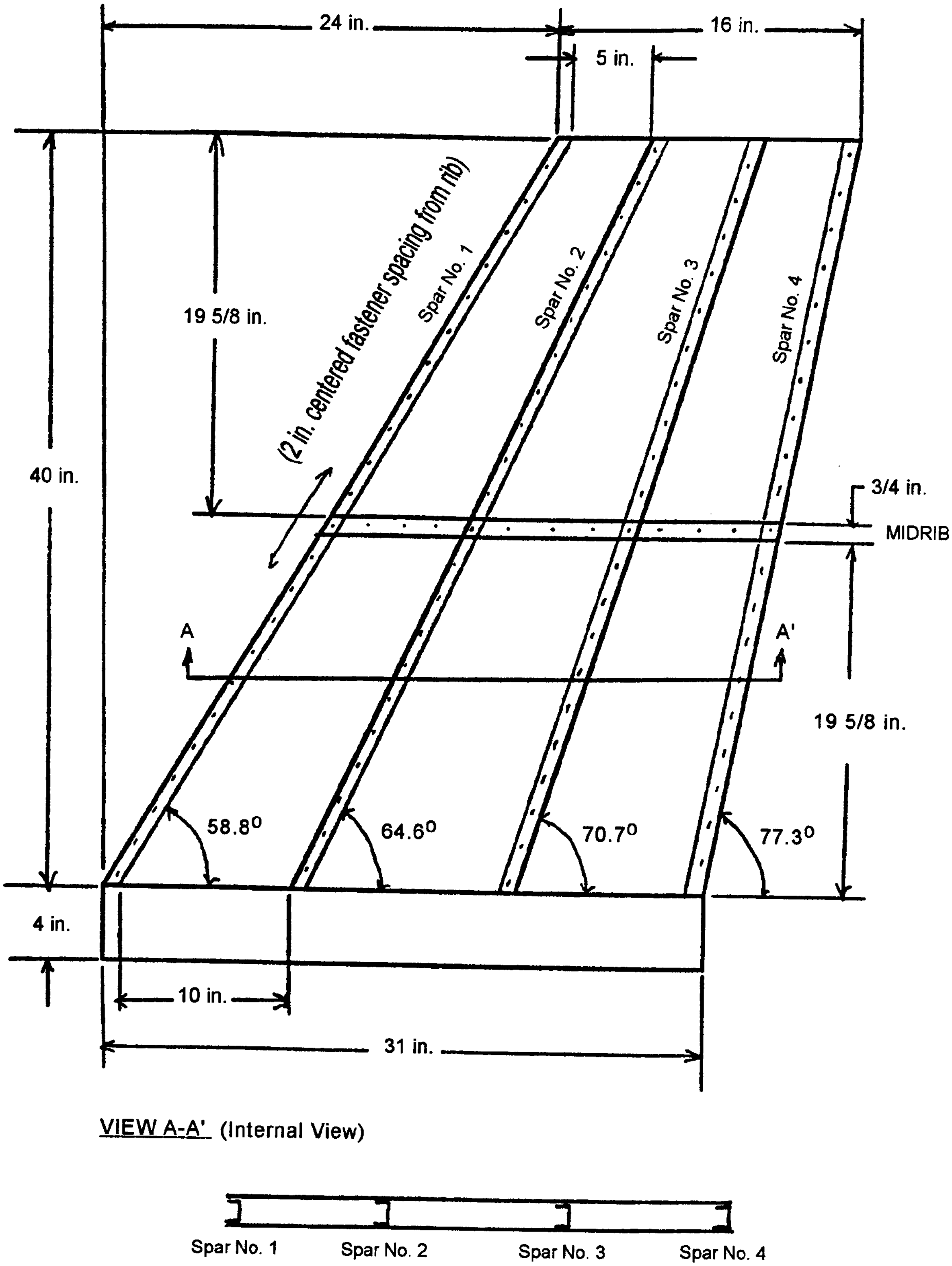


Figure A-1
HALF-SCALE F/A-18 VERTICAL TAIL TEST BED

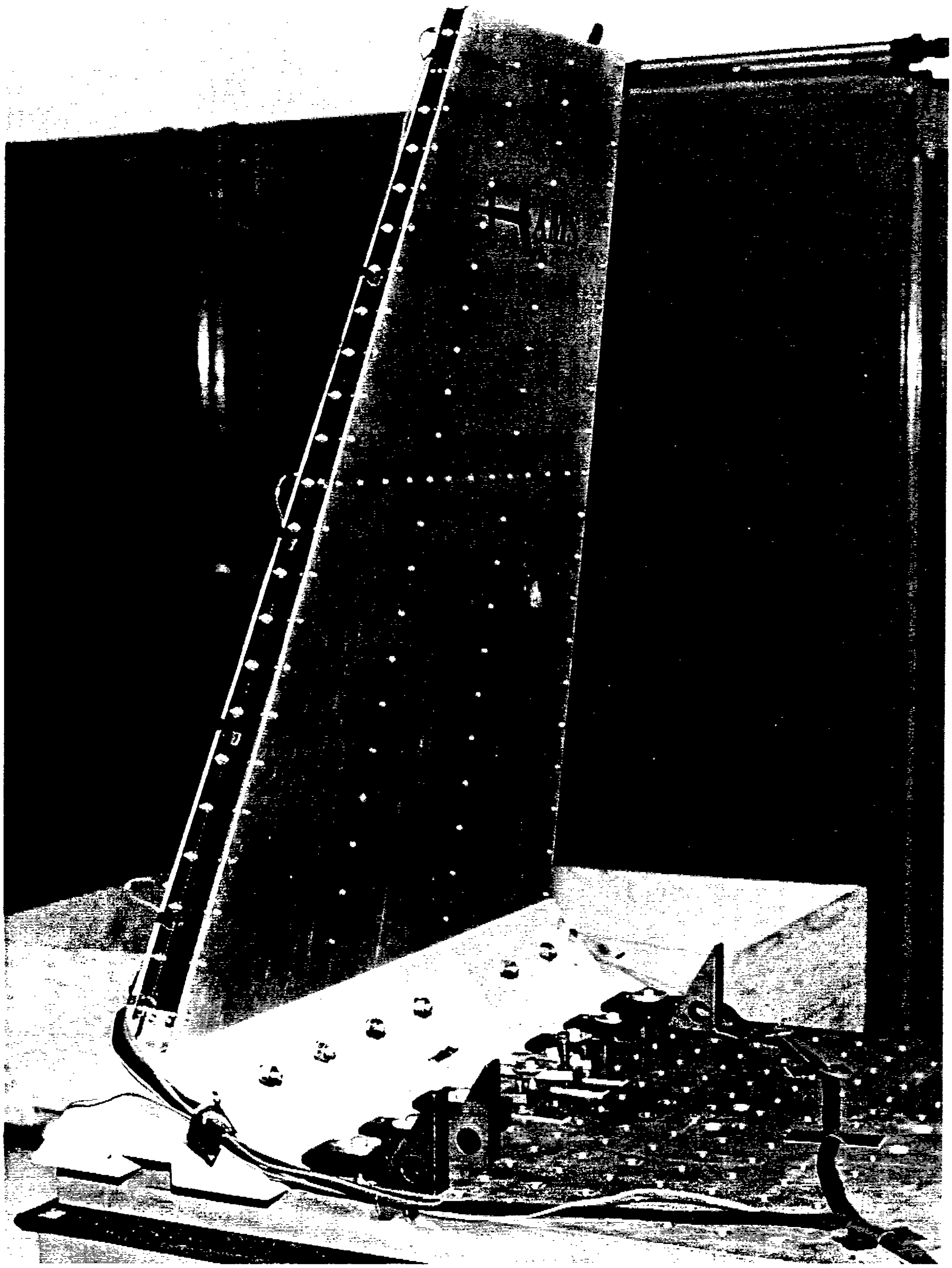


Figure A-2
TEST BED WITH DAMPED COMPOSITE SPARS

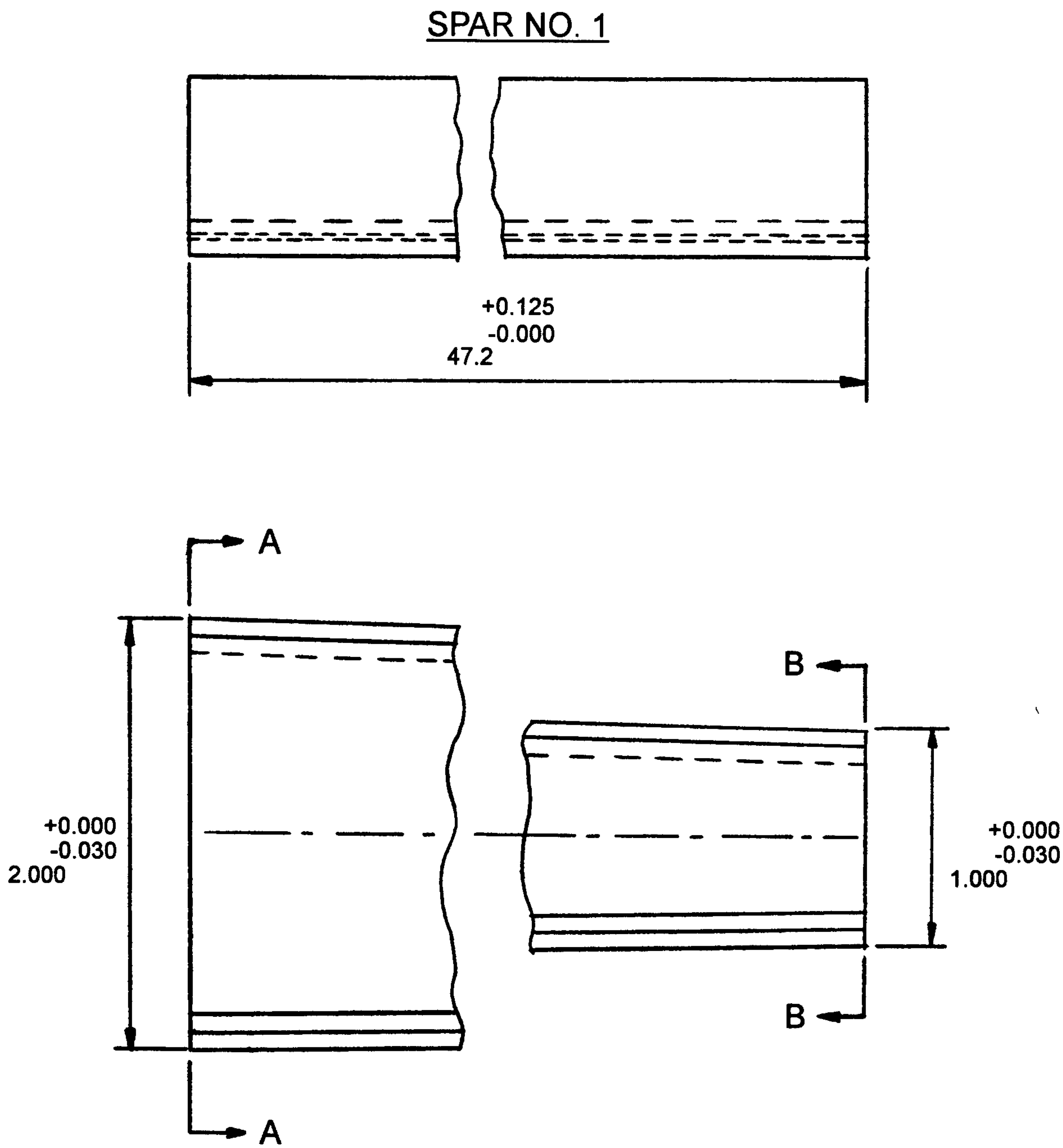
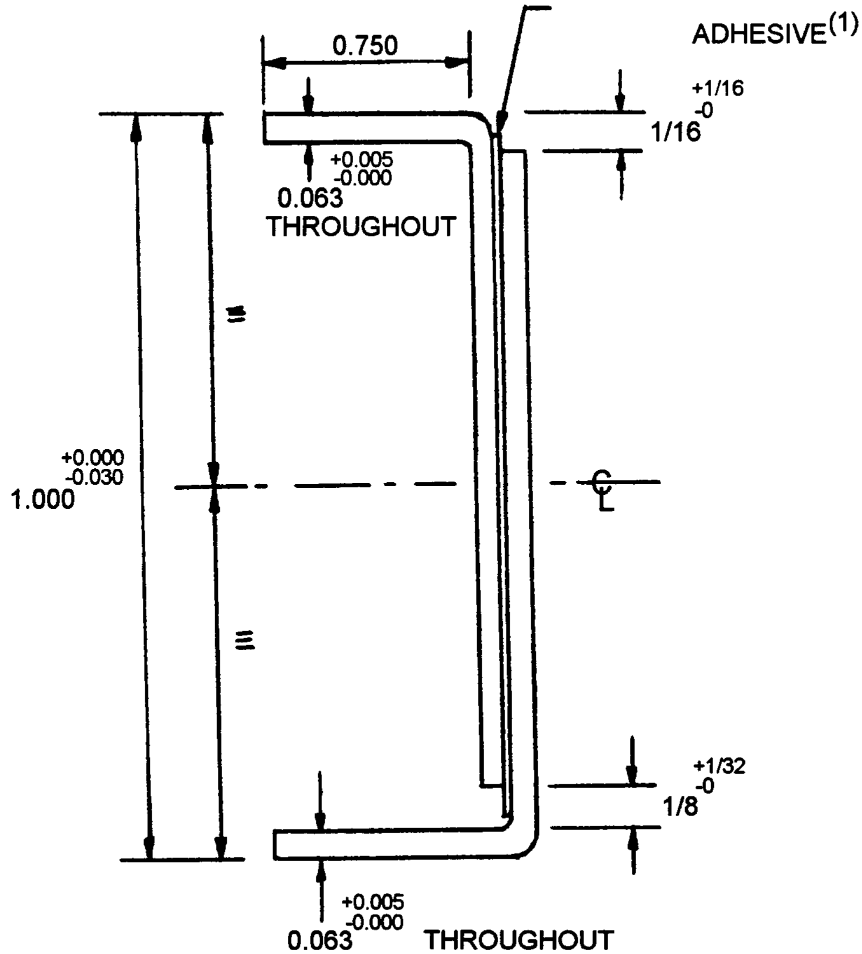


Figure A-3
DAMPED SPAR DESIGN



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NOTES: (1) ADHESIVE LAYER EXTENDS OUT OF THE END OF EACH ANGLE SECTION.

(2) FOR SEC. AA, REPLACE DIMENSION $1.000^{+0.000}_{-0.030}$ BY $2.000^{+0.000}_{-0.030}$.

Figure A-4
CROSS SECTION OF DAMPED SPAR DESIGN

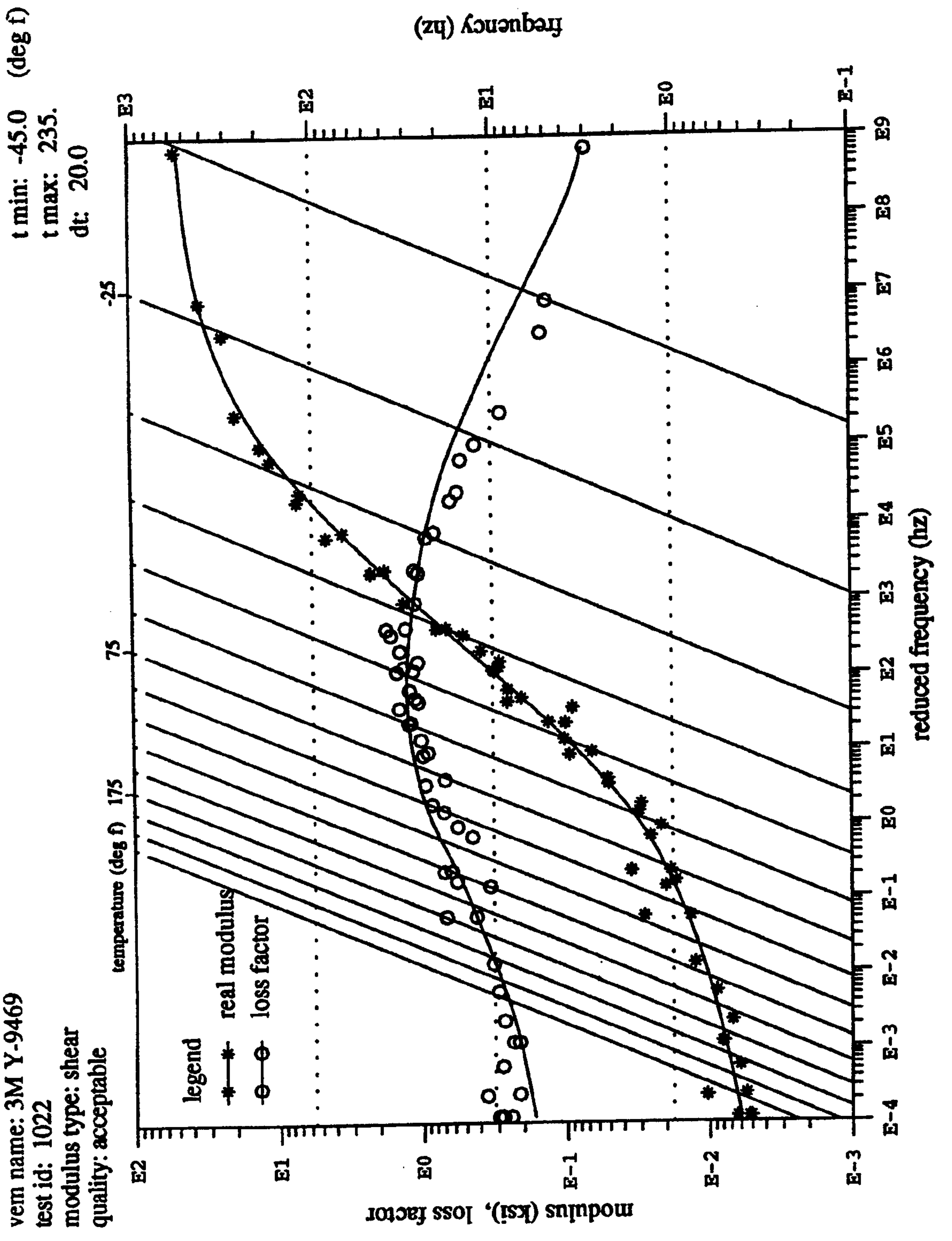


Figure A-5
MATERIAL PROPERTIES OF Y-9469

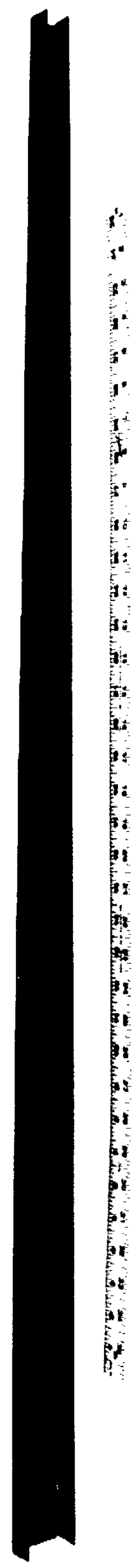


Figure A-6
PHOTOGRAPH OF LEADING EDGE SPAR

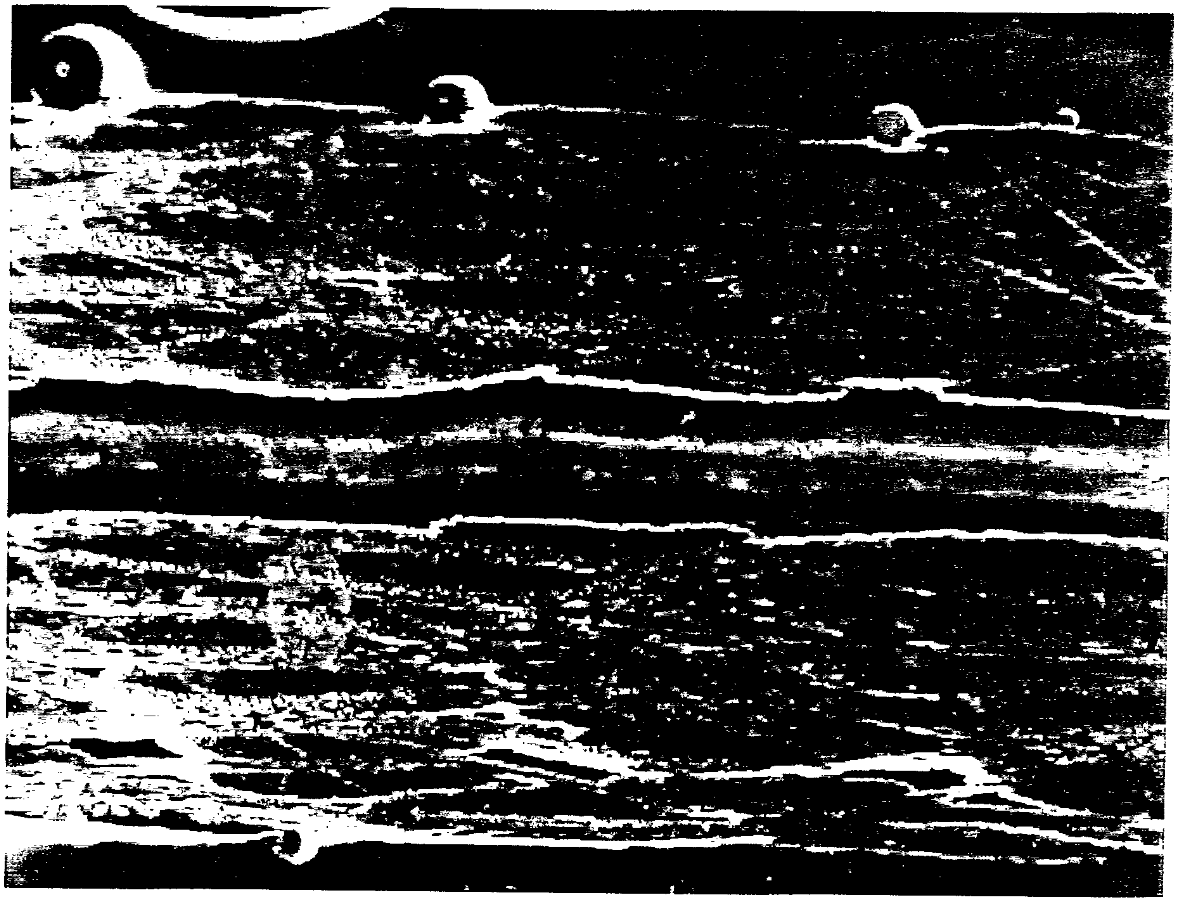


Figure A-7
PHOTOMICROGRAPH OF Y-9469 FILM ADHESIVE AND GRAPHITE/EPOXY FABRIC

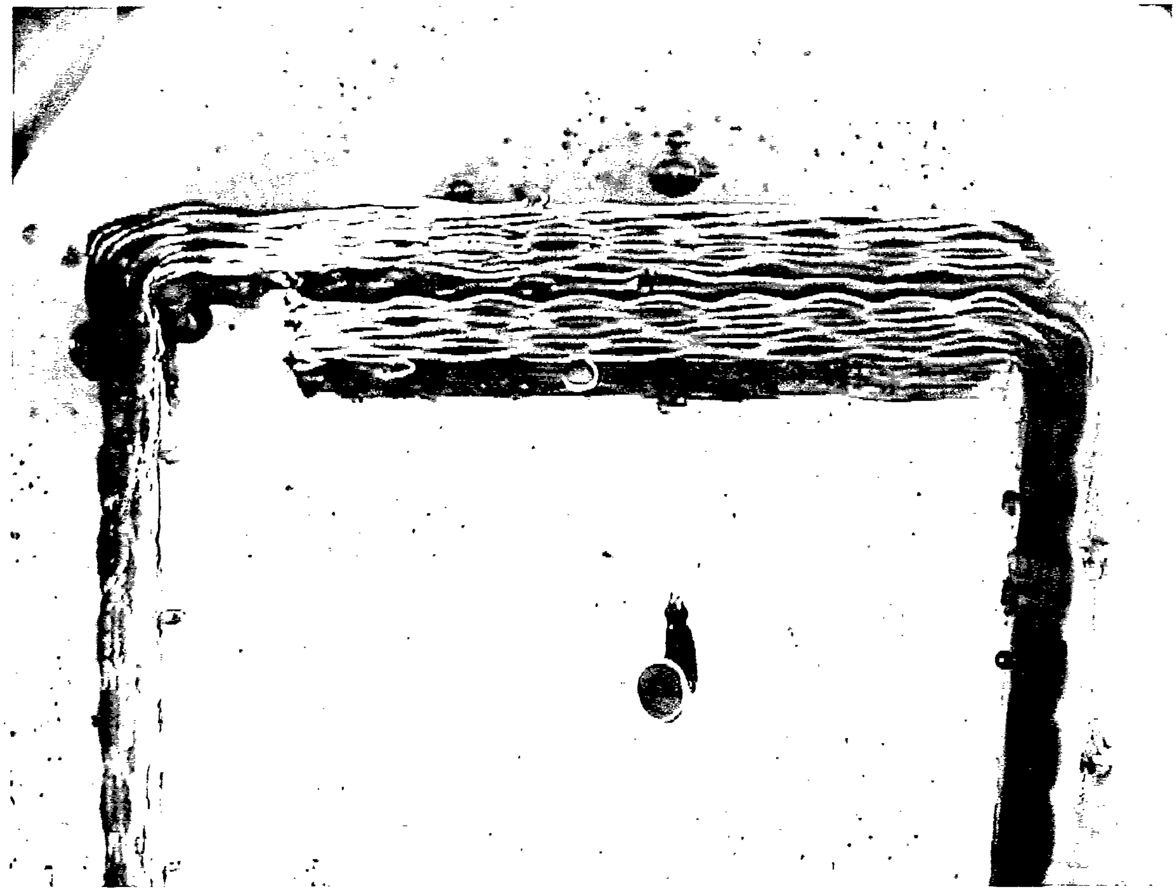
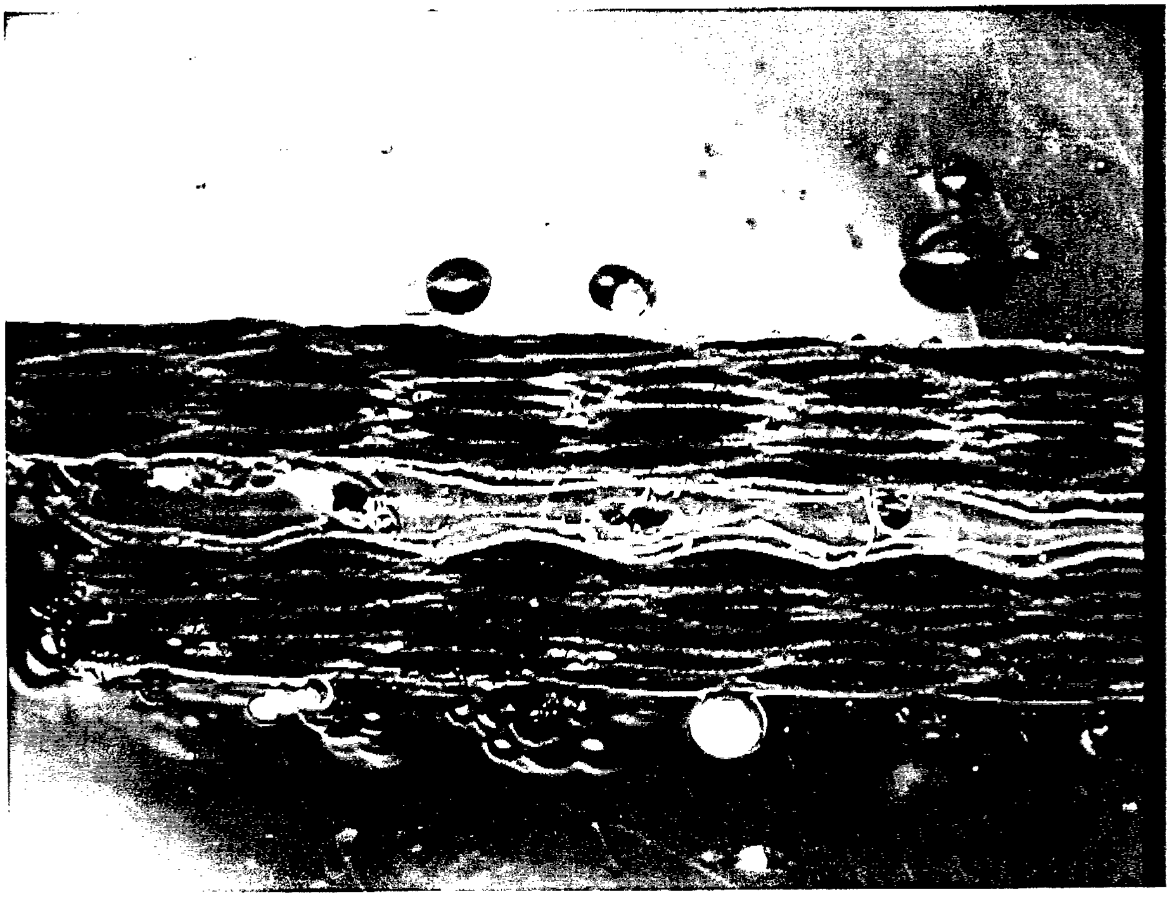


Figure A-8
PHOTOMICROGRAPH OF TRIM FROM 1 IN. END OF DAMPED SPAR



#3 .5 OBJ. .55 MAG MC AIR SPAR

Figure A-9
SURFACE VOIDS IN TRIM (1 IN. END)

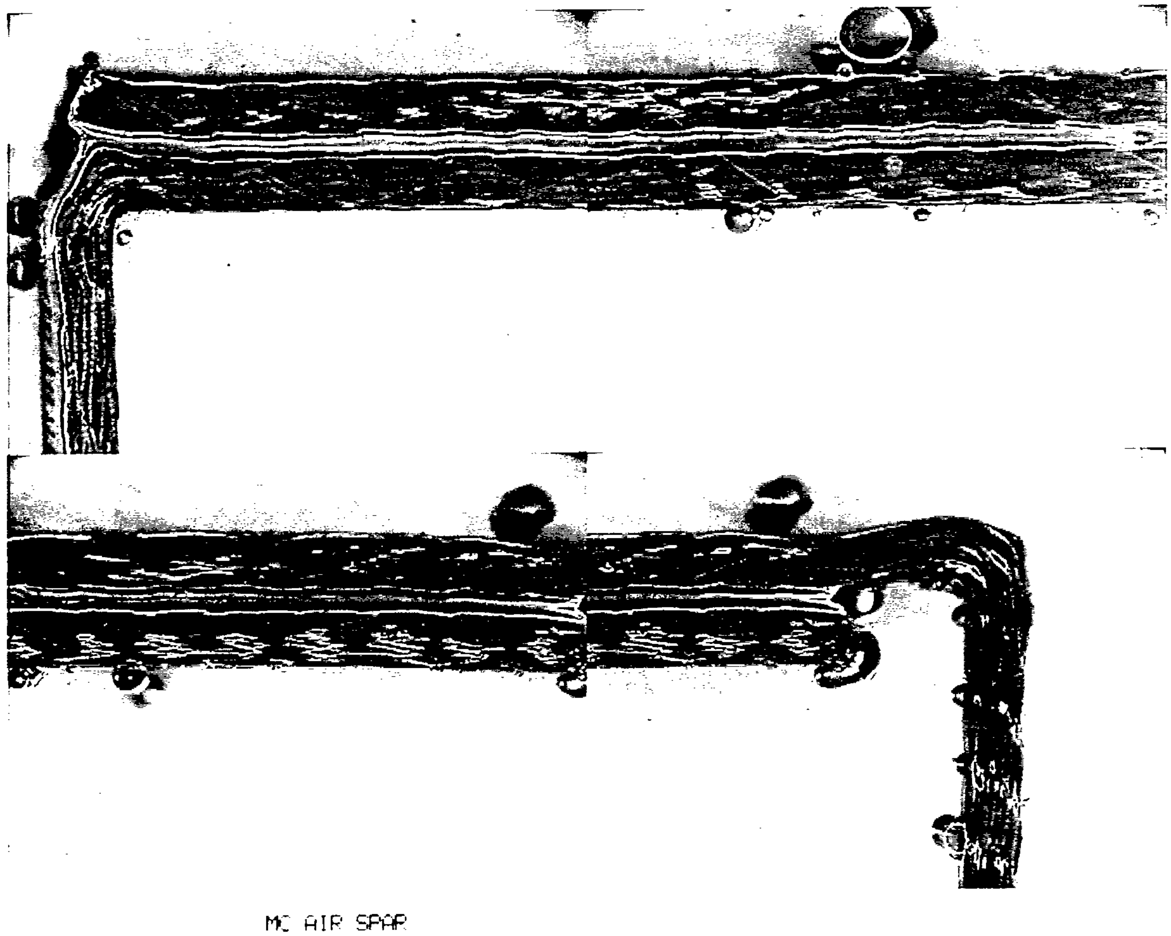
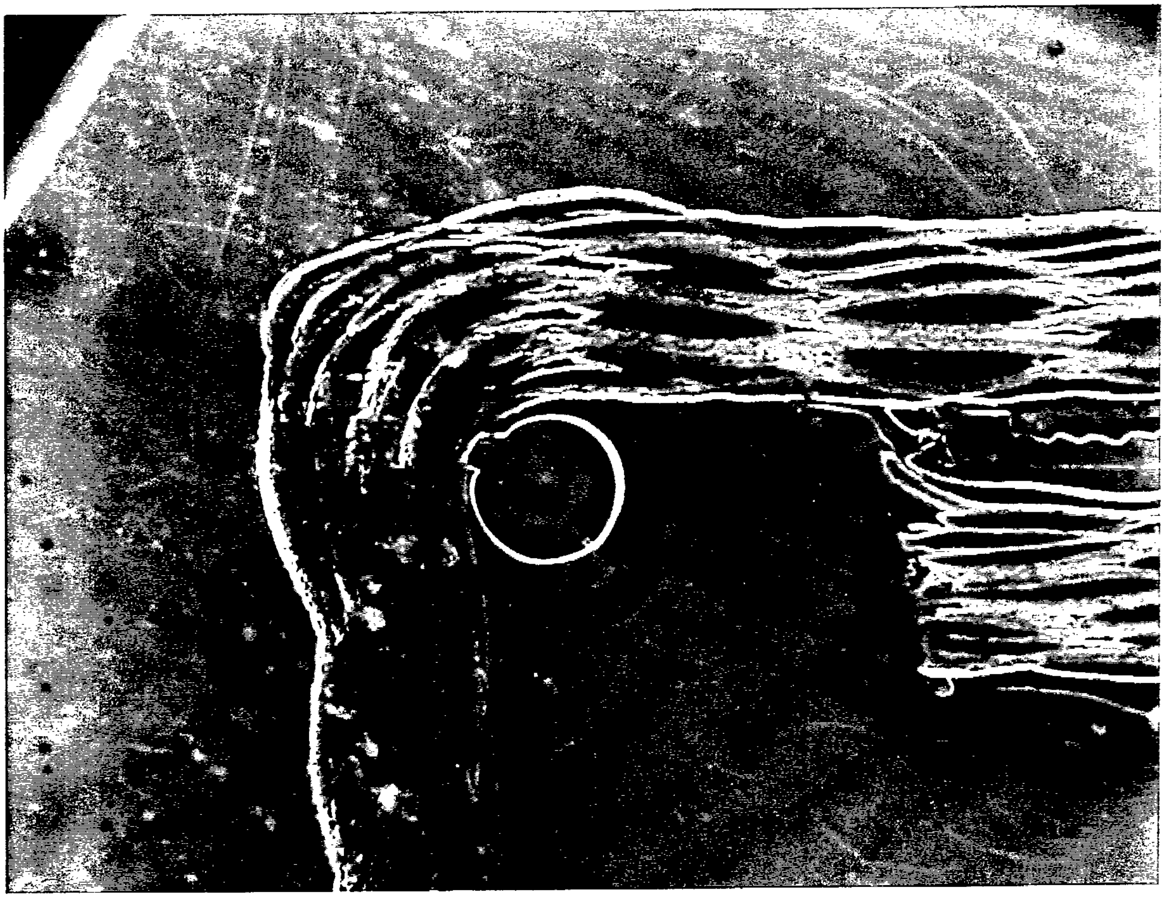


Figure A-10
PHOTOMICROGRAPH OF TRIM FROM 2 IN. END OF DAMPED SPAR

NC AIR SPAR

Figure A-11
SUBSURFACE VOID IN TRIM (2 IN. END)



#3 .5 OBJ. .55 MAG MC AIR SPAR

Figure A-12
PHOTOMICROGRAPH OF TRIM FROM 1 IN. END OF DAMPED SPAR

Figure A-13
PHOTOMICROGRAPH OF TRIM FROM 1 IN. END OF DAMPED SPAR

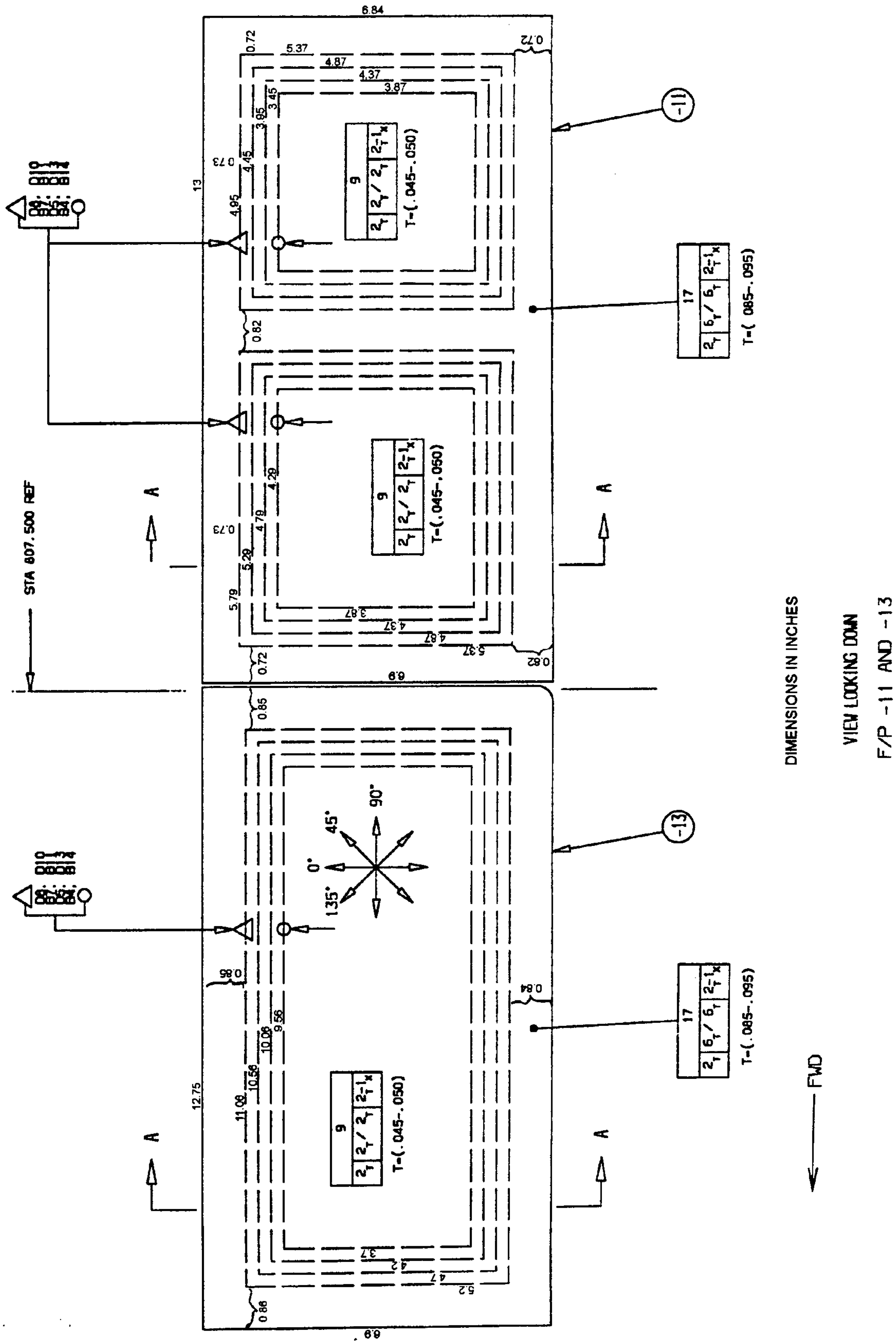


Figure A-14
DESIGN DRAWING FOR DAMPED SKIN PANEL

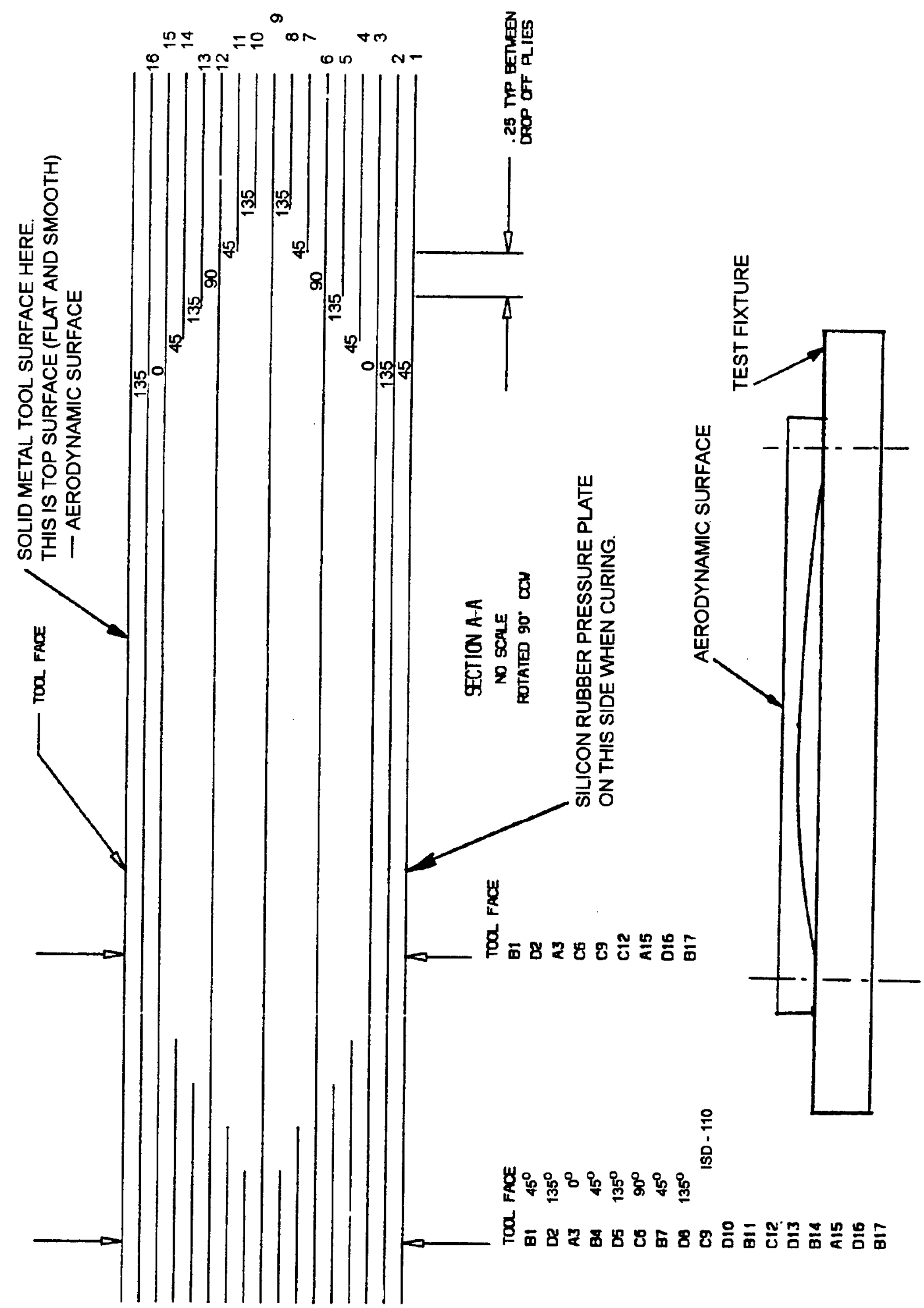


Figure A-15
DESIGN DRAWING FOR DAMPED SKIN PANEL

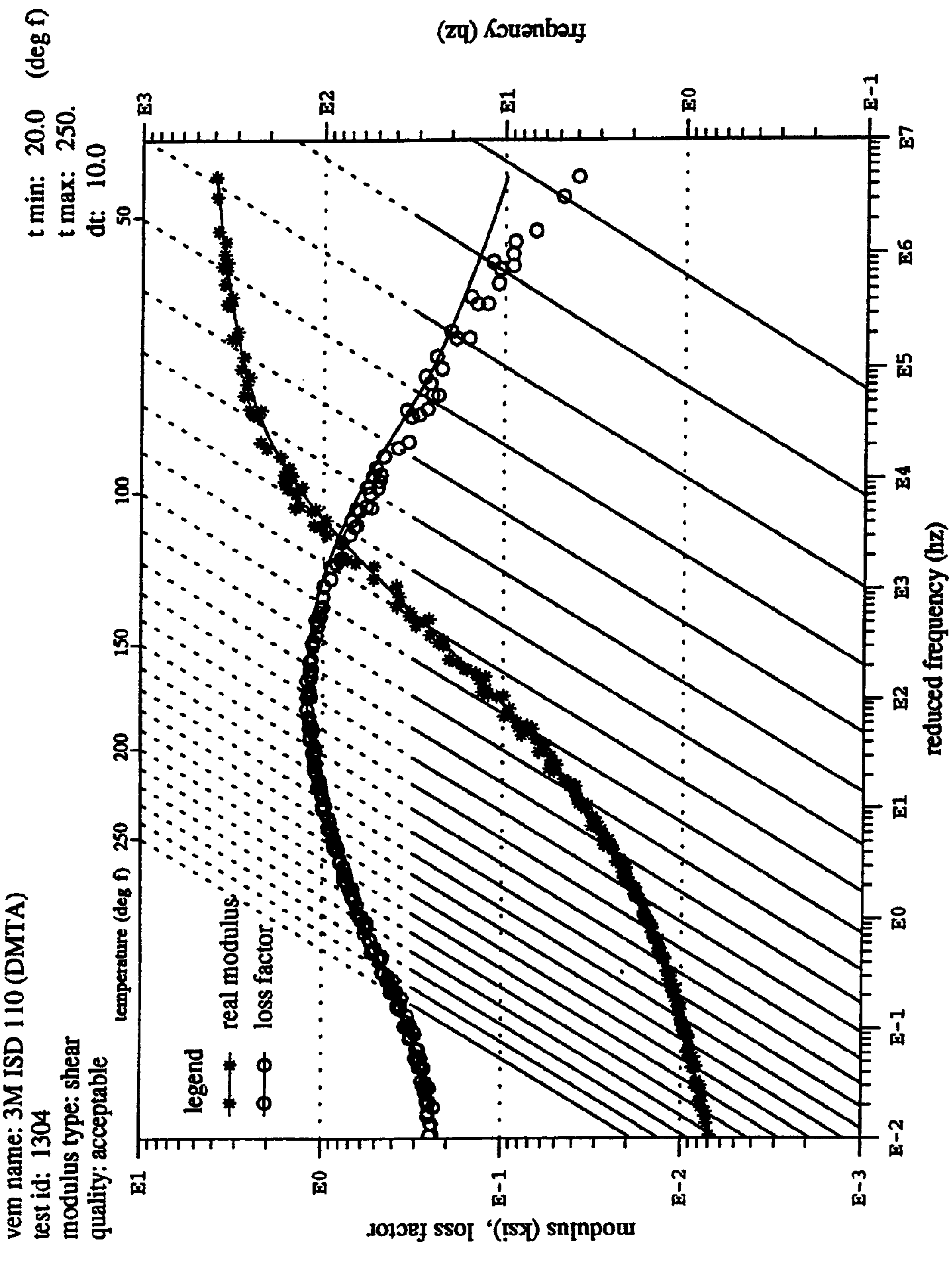


Figure A-16
MATERIAL PROPERTIES OF ISD-110

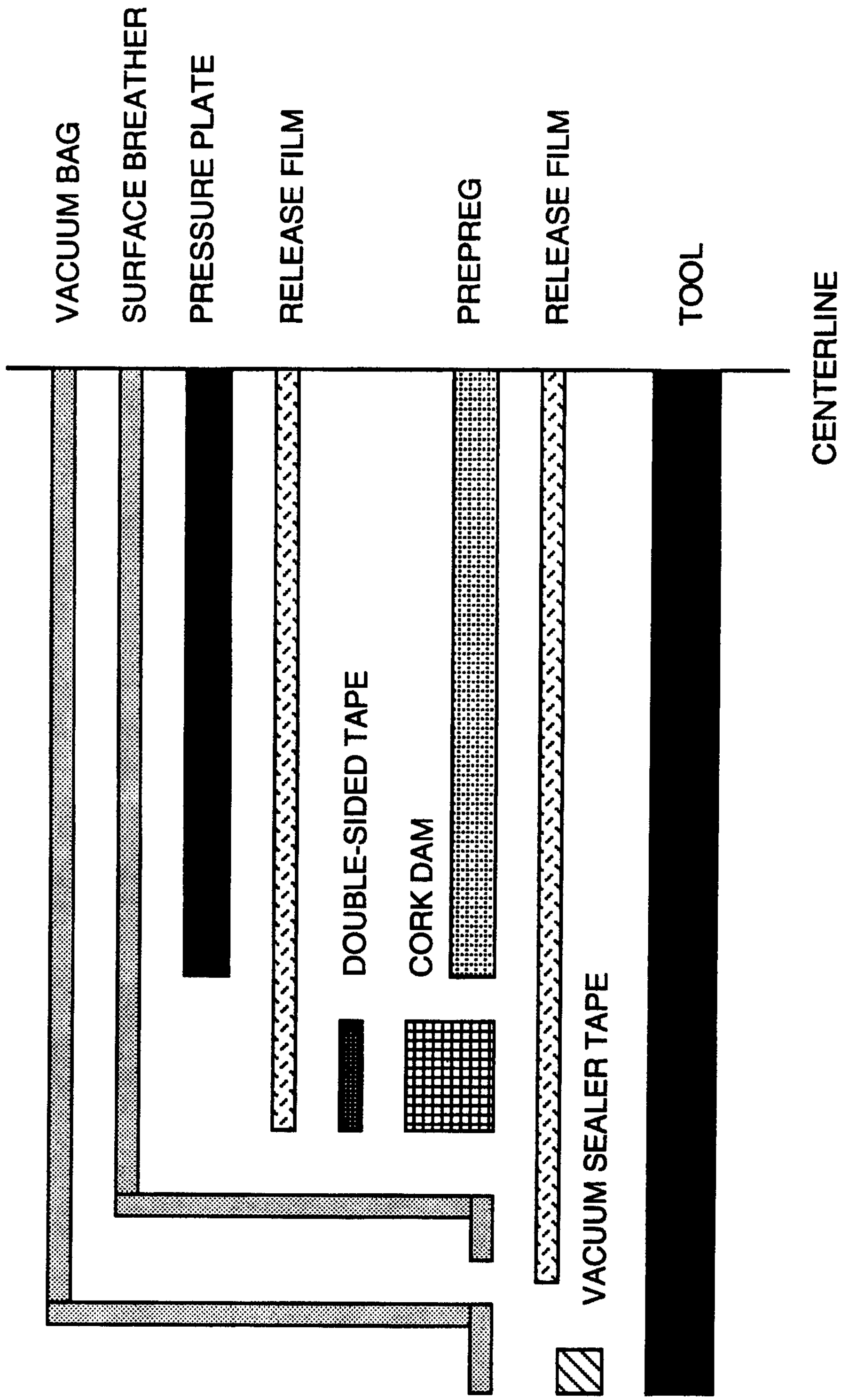


Figure A-17
BAGGING ORDER

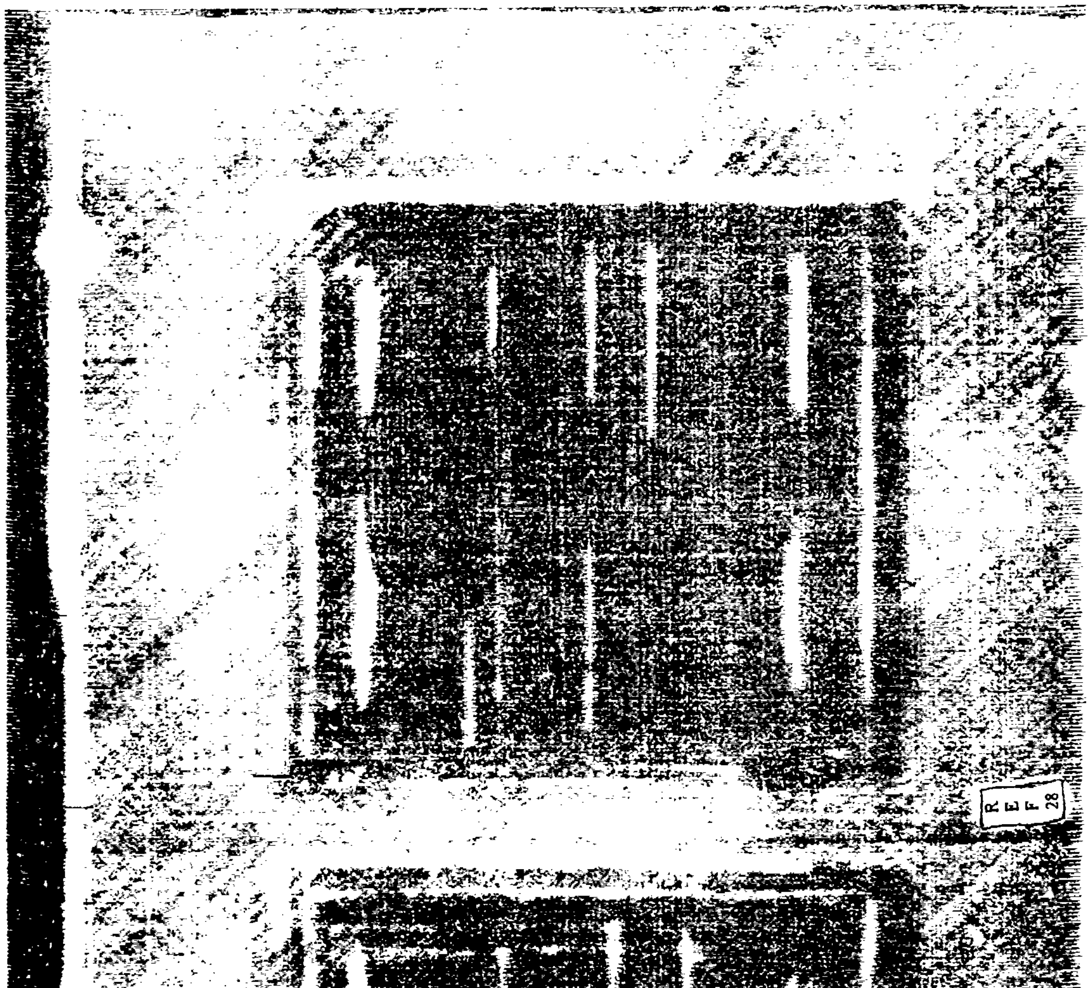
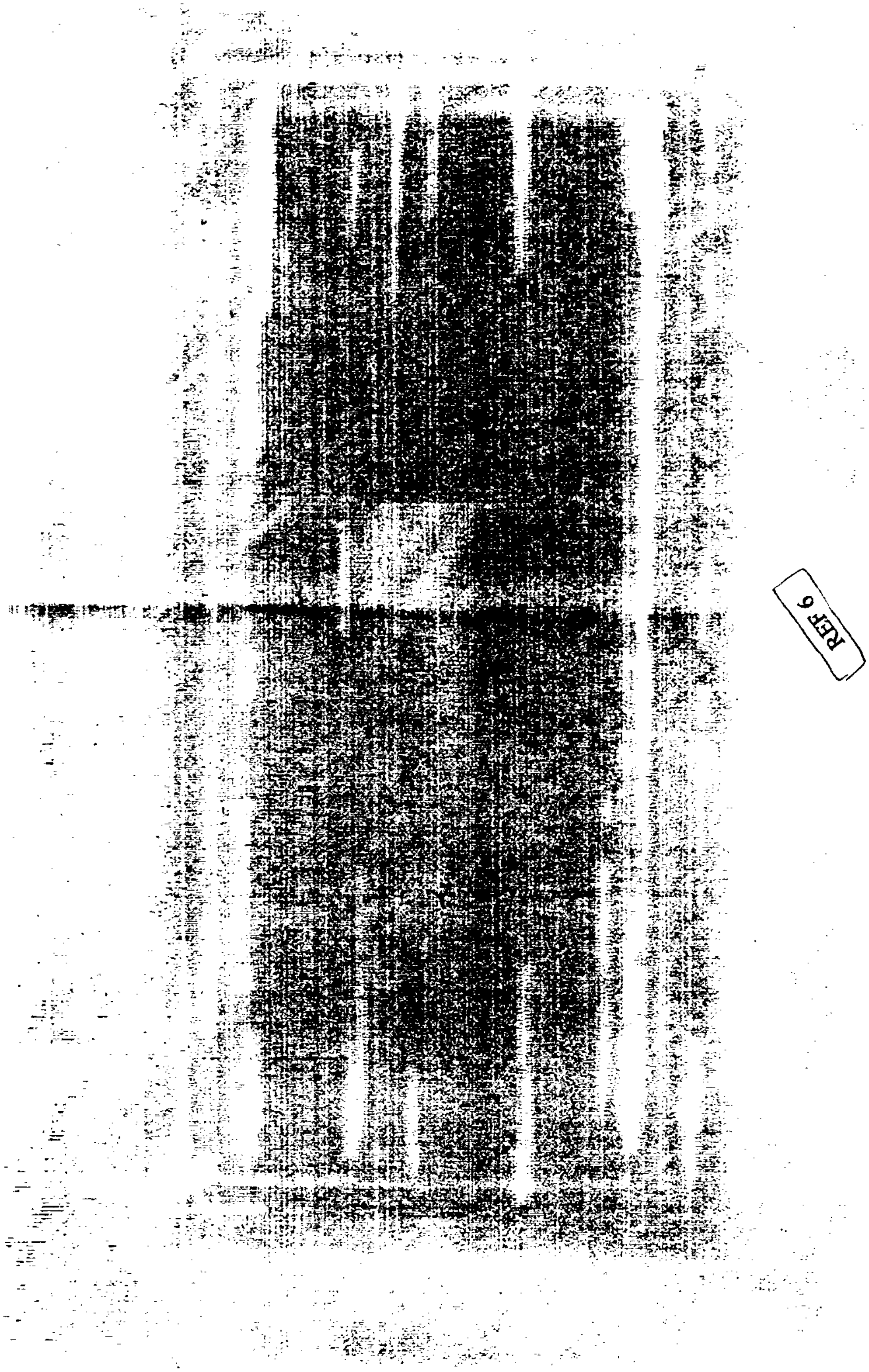


Figure A-18
C-SCAN OF DAMPED PANEL, TWO DAMPING SECTIONS



REF 6

Figure A-19
C-SCAN OF DAMPED PANEL, ONE DAMPING SECTION

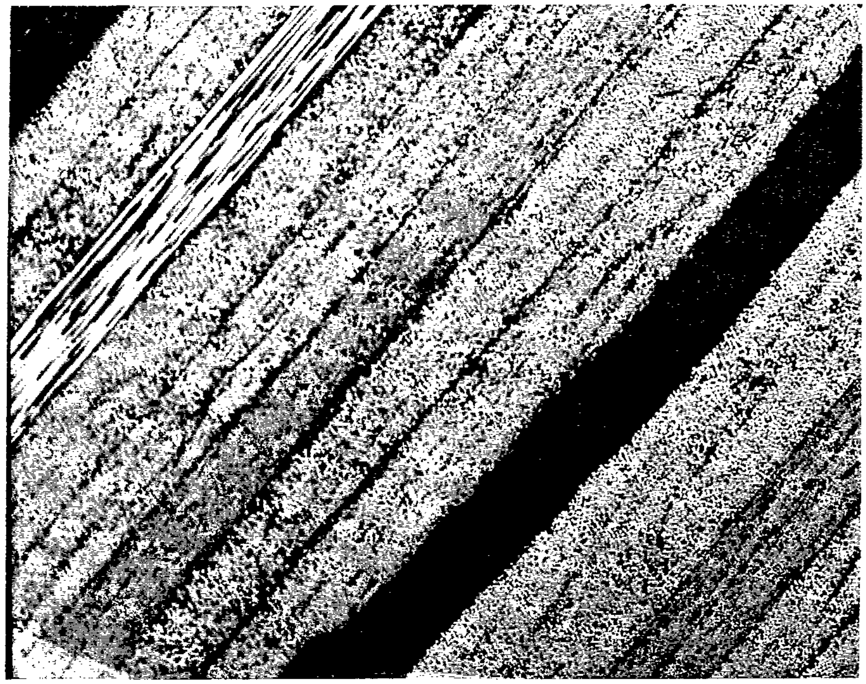
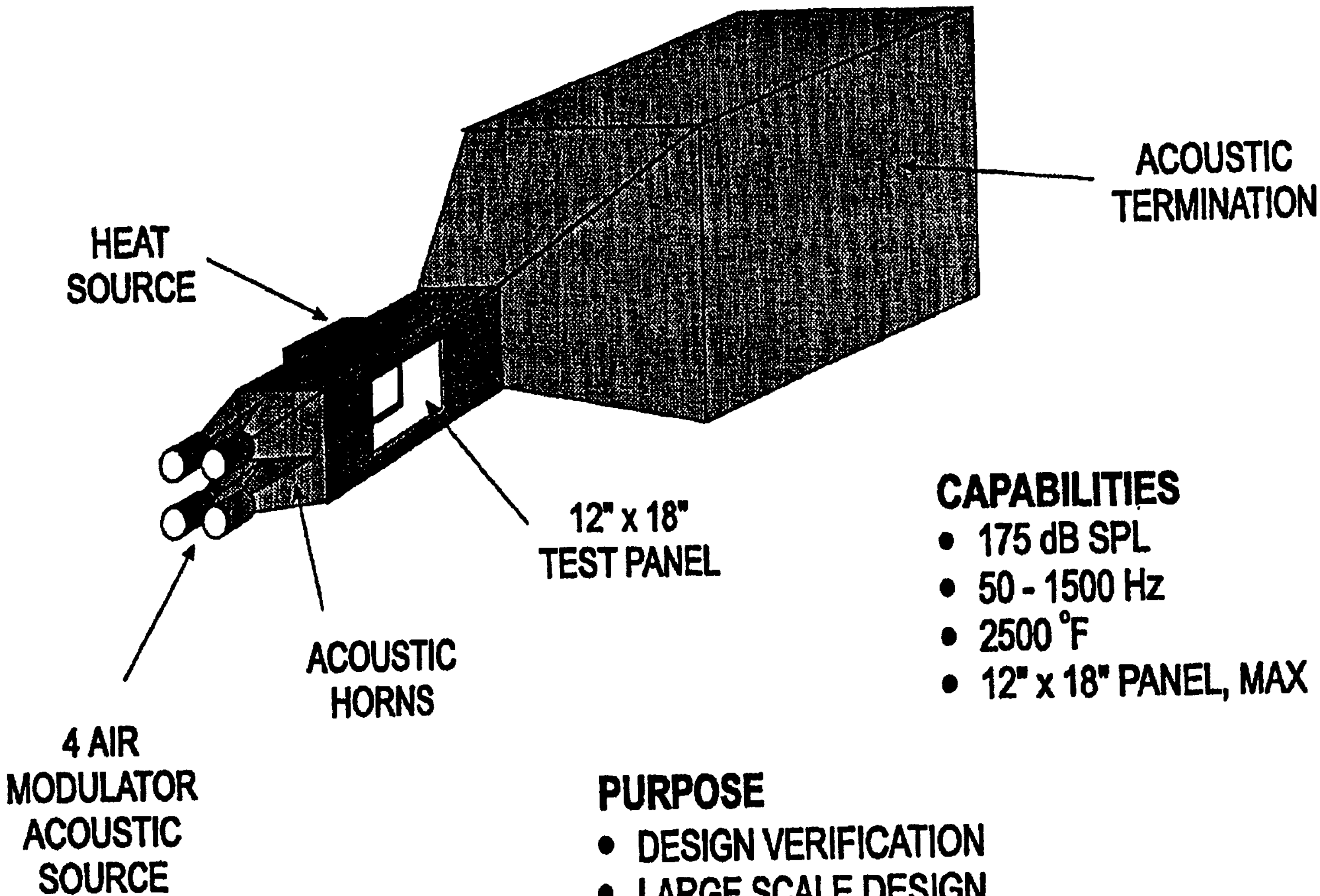


Figure A-20
PHOTOMICROGRAPH OF IM7/977-3 AND ISD-110



CAPABILITIES
- 175 dB SPL
- 50 - 1500 Hz
- 2500 °F
- 12" x 18" PANEL, MAX

PURPOSE
- DESIGN VERIFICATION
- LARGE SCALE DESIGN
- TESTING OF SMALL PANELS

Figure A-21
HIGH TEMPERATURE ACOUSTIC SUBELEMENT CHAMBER

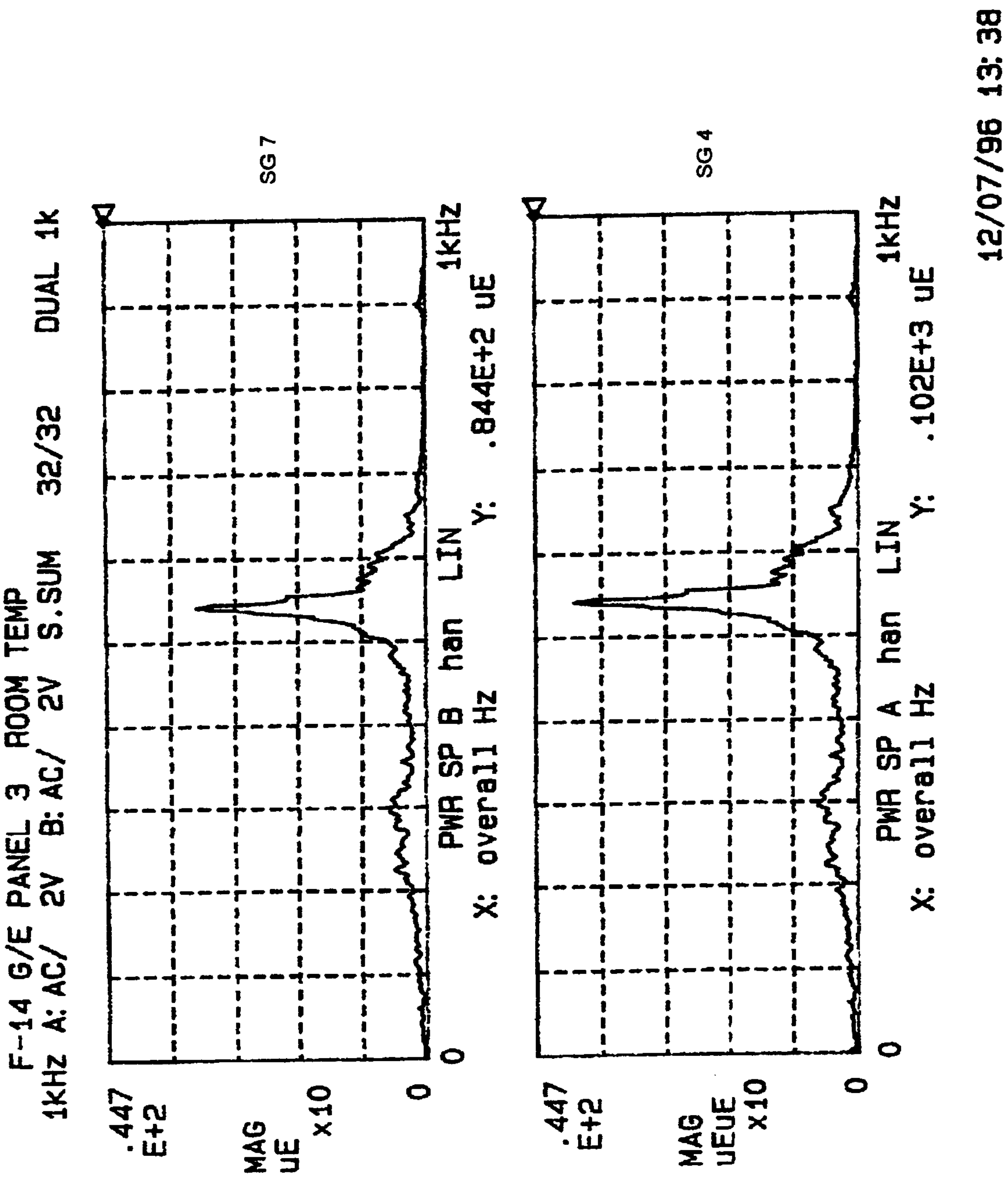


Figure A-22
FREQUENCY RESPONSE, UNDAMPED PANEL

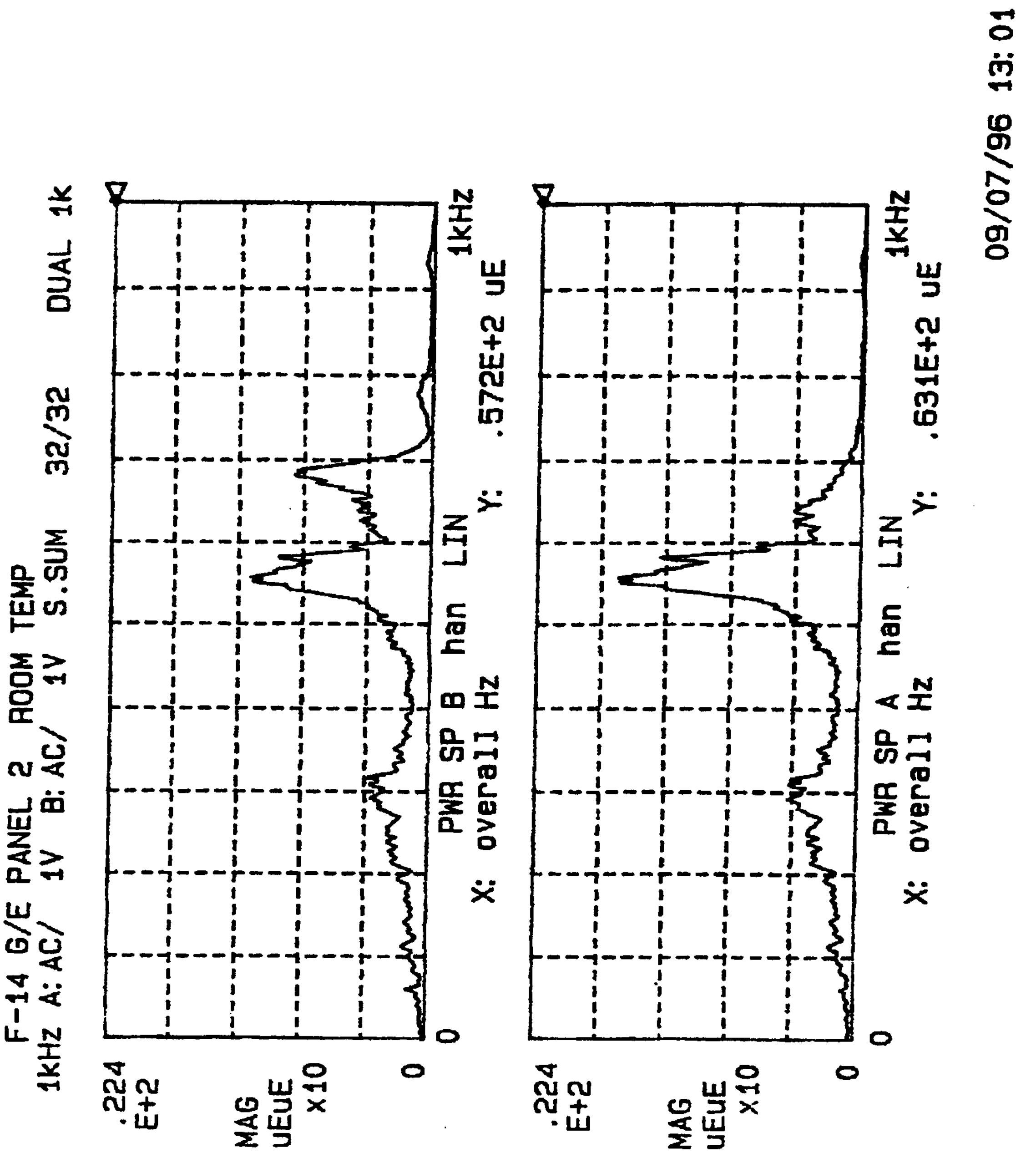


Figure A-23
FREQUENCY RESPONSE, DAMPED PANEL

APPENDIX B
TABLES

Table B-1
MODAL PROPERTIES OF THE LEADING EDGE SPAR

Test Condition	Cantilever Test with Instrumented Force Hammer			
	First Mode		Second Mode	
	Frequency (Hz)	Loss Factor (%)	Frequency (Hz)	Loss Factor (%)
Strike on Minor Axis	14.5	4.4	87.5	3
Strike on Major Axis	26	4.1	97	5.7

Table B-2
MODAL SURVEY (FORCE HAMMER TEST)
PRIMARY TORQUE BOX MODES
(Aluminum Skins with Composite Spars)

Mode Shape	All-Aluminum (1992)		One Damped Spar (1994) AF-32		Two Damped Spars (1995) AF-32 & Y-9469	
	Frequency (Hz)	Loss Factor (%)	Frequency (Hz)	Loss Factor (%)	Frequency (Hz)	Loss Factor (%)
First Bending	53.5	0.44	47.3	1.56	50.3	1.30
First Torsion	120	0.36	118	1.58	111	4.32
Second Bending	189	1.44	181	1.71	-	-
Second Torsion			213	0.840	209	3.62
Chordwise Flex			238	0.812	223	5.14

Table B-3
MODAL SURVEY (SHAKER TEST)
PRIMARY TORQUE BOX MODES
(Aluminum Skins with Composite Spars)

Mode Shape	One Damped Spar (1994)		Two Damped Spars (1995)	
	Frequency (Hz)	Loss Factor (%)	Frequency (Hz)	Loss Factor (%)
"1/10 g Sine Sweep"				
First Bending	47.1	1.04	50.3	6.0
First Torsion	118	0.55	111	3.6
Second Bending	180	1.18	-	-
Second Torsion	213	1.01	209	6.73
Chordwise Flexure	238	0.234	223	5.24
"1 g Sine Sweep"				
First Bending	46.3	2.18	50.3	3.88
First Torsion	117	1.13	111	5.14
Second Bending	178	1.66	-	-
Second Torsion	212	2.07	209	6.46
Chordwise Flexure	237	0.406	223	-

Table B-4
MODAL SURVEY (SHAKER TEST WITH POSTPROCESSING OF THE DATA)
PRIMARY TORQUE BOX MODES
(Aluminum Skins with Composite Spars)

Mode Shape	Frequency (Hz)	Loss Factor (%)
"1/10 g Sine Sweep"		
First Bending	49.6	2.0
First Torsion	111	4.5
Second Bending	172	4.7
Second Torsion	209	5.7
Chordwise Flexure	-	-
"1 g Sine Sweep"		
First Bending	47.6	2.7
First Torsion	110	6.5
Second Bending	171	5.2
Second Torsion	210	5.7
Chordwise Flexure	-	-

Table B-5
SUMMARY OF TEST DATA

Specimen	No Damped Spars	One Damped Spar	Two Damped Spars	Two Damped Spars
Test Method	Impact Hammer	Impact Hammer	Shaker, 1/10 g Sine Sweep	Shaker, 1 g Sine Sweep
Damping Materials	None	AF-32	AF-32 and Y-9469	AF-32 and Y-9469

Mode	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)
First Bending	53.5	47.3	49.6	47.6
First Torsion	120	118	111	110
Second Bending	189	181	172	171
Second Torsion		213	209	210

Mode	Loss Factor (%)	Loss Factor (%)	Loss Factor (%)	Loss Factor (%)
First Bending	0.44	1.56	2.0	2.7
First Torsion	0.36	1.58	4.5	6.5
Second Bending	1.44	1.71	4.7	5.2
Second Torsion		0.84	5.7	5.7

Table B-6
MATERIAL PROPERTIES OF IM7/977-3 AT 240°F
(IM7/977-3 Tape (5.6 mils))

Material Property	Value
Axial Modulus (MSI)	22.5
Transverse Modulus (MSI)	0.930
Axial Shear Modulus (MSI)	0.430
Transverse Shear Modulus (MSI)	0.260
Axial Poisson's Ratio	0.300
Axial Loss Factor	0.00434
Transverse Loss Factor	0.00628
Shear Loss Factor	0.00708
Weight Density (pci)	0.0570

Table B-7
DAMPING PROPERTIES OF ISD-110 AT 240°F

Frequency (Hz)	Shear Modulus (psi)	Loss Factor
100	16.1	0.466
200	18.2	0.523
400	21.0	0.586
600	23.0	0.625
800	24.6	0.654
1000	26.0	0.677
1200	27.3	0.696
1400	28.4	0.712
1600	29.5	0.726
1800	30.4	0.739
2000	31.3	0.751

Table B-8
PROCESS CYCLE FOR IM7/977-3

Step	Procedure
1	Place the part in the autoclave and apply a vacuum of at least -26 in. Hg. Perform a leak check.
2	Pressurize the autoclave to 85 psi.
3	At a ramp rate of 1 to 2°F per minute, raise the temperature to 290°F (±5°F).
4	Dwell at 290°F (±5°F) for 1 hr (±5 min). At the beginning of the dwell, vent the vacuum bag and increase the autoclave pressure to 100 psi.
5	At a ramp rate of 0.5 to 1°F per minute, raise the temperature to 355°F (±5°F).
6	Dwell at 355°F (±5°F) for 6 hr (±10 min).
7	Cool at a rate of 0.5 to 1°F per minute to below 150°F.
8	Vent the autoclave to atmosphere.
9	End the autoclave run and remove the part.

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